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A Modified Delay-Based Spacing Policy for Heterogeneous Vehicle Platoons

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Abstract— **This paper proposes a modification to a delay-based spacing policy for heterogeneous platooning applications. To this end, the approach to spatially track a reference speed profile time-shifted by a certain delay is augmented by a spatial offset that ensures safe operation over a full platoon mission, including standstill. A matching linear controller is derived to compensate for heterogeneous vehicle dynamics. By means of homogenization, the different dynamic ranges of platoon members are considered. Finally, further performance features are realized through constrained control, such as the restriction to a permissible acceleration range, limited catch-up speed and safe braking distances.**

I. Introduction

Platooning is understood as the virtual coupling of several vehicles to yield a coordinated formation. If the members of the platoon share goals, they are able to cooperate. To this end, vehicles share information on their vehicle state and control objectives. Cooperation is key to drive vehicles in close formation, thus enabling them to exploit the slipstream effect for reduced air drag, which can lower the control effort and eventually fuel consumption. Furthermore, driving at small inter-vehicle distances increases traffic throughput on limited infrastructure.

From the viewpoint of control engineering, challenges arise from the fact that no two vehicles are identical. Especially when considering applications in the public sector, such as the transportation of goods for humanitarian relief or in the private sector with large vehicle fleets, heterogeneity in the platooning system arises from different vehicle types, shapes of vehicle bodies, payload etc. Hence, heterogeneous vehicle platoons need to be considered. Fig. 1 shows the aforementioned situation. The members of a heterogeneous platoon are grouped together and share information via communication links that enable them to lower inter-vehicle distances and therefore the overall length of the platoon.

The paper is structured into an overview of the related work in section II, followed by the preliminaries and used models throughout this paper in section III. A controller is designed, implementing a modified delay-based spacing policy, in section IV. The stability of the control system is considered in section V. The linear controller is then enhanced by our homogenization scheme and augmented by means of constrained control to account for non-linear features of the platooning system in section VI, based on our findings in [1] and [2]. Finally, the proposed control scheme is evaluated by means of simulation in section VII.

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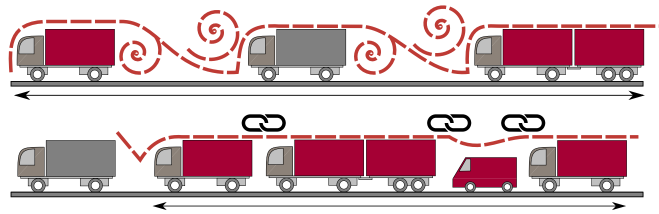

Fig. 1. Heterogeneous vehicle platoon

II. Related Work

In [3] a linear controller for predecessor following (PF) of a homogeneous vehicle platoon has been presented and evaluated. The spacing policy implemented is the constant time headway (CTH) policy. The desired spacing $d_{\text{des},i}$ is based on a constant offset at standstill r_0, and a speed (v) dependent term, which is scaled by the headway h:

$$d_{\text{des},i}(t) = r_{0,i} + h_i v_i(t) \tag{1}$$

It has been shown that this spacing policy allows for stable platooning control and has since been well researched, broadened and applied. For example, in [4] an evolved set of controllers has been presented that account for different actuation lags of the platoon members. However, with their linear design, these controllers did not take actuator limitations into account.

As safety in road transportation is paramount, one could employ invariance control such as in [5]. Therein, a Lyapunov controller implements the CTH policy (1) on a non-linear system model. Constraints using invariance theory were formulated into control barrier functions (CBF) to yield safe operation, in particular collision avoidance. These conditions were cast into an optimization problem and solved in a quadratic program. Yet, the CBF approach exhibits undesired effects when constraints are violated. In [6] zeroing control barrier functions (ZBF) were introduced to the platooning application. One advantage over CBF is the capacity to yield robust responses to disturbances and *unsafe* initial conditions.

To harness the benefits of a linear design, [7] explored, how a nominal controller output can be constrained to oblige to limiting conditions. In particular, dynamic environments for human-robot interactions were researched. However, the flexible structure of the design is applicable to other classes of systems.

In contrast to the aforementioned CTH spacing policy, a delay-based spacing policy was introduced in [8]. The control objective is to track a reference vehicle speed in space,

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rather than in time. This approach is very promising, as road features like inclines and speed limits impose different set speeds depending on the position along the platooning route and are hence spatially rooted. To this end, the reference position is defined as:

$$p_i^{\text{ref}}(t) = p_{i-1}(t - \Theta) \tag{2}$$

with adjusted notation. Thus, the reference position p_i^{ref} of a vehicle with index i (i. e. V_i) tracks the time-delayed trajectory of its predecessor V_{i-1}. The time delay (or gap) is chosen as $\Theta > 0$. The authors of [8] demonstrate that for $v > 0$ *spatial* tracking of a homogeneous platoon can be achieved, so that

$$\tilde{v}_i(p) = \tilde{v}_{i-1}(p) = \tilde{v}^{\text{ref}}(p)\ . \tag{3}$$

In contrast to the time-based definition of (2), (3) is defined in the spatial domain, indicated by speed over position $\tilde{v}(p)$. With these definitions, the desired position difference, i. e. desired spacing, can be derived as

$$d_i^{\text{ref}}(t) = \int_{t-\Theta_i}^{t} v_{i-1}(\vartheta)\,\mathrm{d}\vartheta\ . \tag{4}$$

The approach was broadened for heterogeneous vehicle platoons by means of exact linearization in [9].

However, it is apparent, that for $v^{\text{ref}} = 0$, the reference position difference (4) also vanishes. Thus, the entire platoon reduces to a single point in space when coming to a halt. Therefore, the reference speed must be lower-bounded to $\min v^{\text{ref}}\theta > L_{\max}$, with $L_{\max}$ denoting the maximum vehicle length across the vehicle string [9]. Forming of a platoon also requires that non-zero vehicle speeds are allowed—even, when a reference in space is not applicable as in (3). Moreover, the approach of a controller design in the spatial domain seems counter-intuitive for real-world dynamic systems that are supposed to deliver an intended behavior at any given moment in time. Relying on a purely spatial definition is also insufficient, as $\tilde{v}^{\text{ref}}(p)$ is not necessarily a bijective function, i. e. a mapping $\tilde{v}^{\text{ref}} : p \to v$ is ambiguous for standstill. This is also supported by [10] in which was demonstrated that real world traffic situations happen in time and not necessarily only at certain positions.

III. Preliminaries

A. Vehicle Model

For a vehicle V_i, the vehicle model is defined as in [2]:

$$\begin{bmatrix} \dot{p}_i(t) \\ \dot{v}_i(t) \\ \dot{a}_i(t) \end{bmatrix} = \begin{bmatrix} v_i(t) \\ a_i(t) \\ -(1/\tau_i)a_i(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1/\tau_i \end{bmatrix} u_i(t) \tag{5}$$

with the state variables position p, speed v, and acceleration of the vehicle body a. The control variable u actuates the engine and is lagged by a time constant τ. These variables are scalar and real (i. e. $\{p, v, a, u, \tau\} \in \mathbb{R}$).

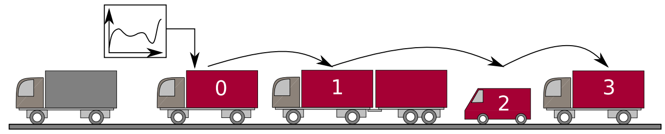

Fig. 2. Reference input and communication topology

B. Platoon Model

A platoon is understood as a string of vehicles that are virtually coupled to coordinate their driving behavior for cooperation and achieve compatible control objectives. With the understanding of a string of vehicles, the focus lies on longitudinal control. If only identical vehicles are considered, the platoon is homogeneous. Heterogeneity arises from composing different vehicle types and dynamics into a platoon, but also from different parameters of its members. Generally speaking, the influence of heterogeneity degrades the platoon performance [11]. The coupling between the members is established by means of (wireless) communication, allowing to share information on vehicle states and trajectories. As such, they are capable to execute joint missions. Missions are defined by reference trajectories that steer the nominal behavior of the platoon. With these reference trajectories, maneuver control can be implemented. Fig. 2 shows a heterogeneous platoon with a reference input for mission control in a cascaded communication topology, here PF.

C. Spacing Policy

The desired distance between members of the platoon is defined by a spacing policy. As discussed in section II, the delay-based spacing policy in the original definition (2)–(4) after [8] has significant drawbacks that render it infeasible for a mission-oriented, real-world application. However, the benefits of spatial tracking of a reference speed profile shall be maintained. To this end, the spacing policy is modified to ensure a strictly positive desired inter-vehicle distance, including at standstill. The reference trajectory is understood as tracking of passage points in time along the route

$$p^{\text{ref}} : t \to p\ . \tag{6}$$

The function p^{ref} shall be (not strictly) monotonously increasing. Its time-derivatives define the reference speed, and reference acceleration.

IV. Control Design

In this section, a distributed controller is presented which implements a modified delay-based spacing policy for mission control for heterogeneous platoons of vehicles with different τ_i.

A. Control Problem

For vehicle followers $V_i, i = 1, \ldots, N-1$ the desired position is delayed by Θ_i in time and spatially shifted by a positive buffer distance $R_i > 0$. The delay-based formulation

(2) to track the trajectory of a predecessor V_h (with $h = i-1$) then yields:

$$p_i^{\text{ref}}(t) = p_h(t-\Theta_i) - R_i \tag{7}$$

The reference position difference (i. e. the desired spacing) (4), thus becomes:

$$\begin{aligned} d_i^{\text{ref}}(t) &= p_h(t) - p_h(t-\Theta_i) + R_i \\ &= \int_{t-\Theta_i}^{t} v_h(\vartheta)\,\mathrm{d}\vartheta + R_i \end{aligned} \tag{8}$$

The position error for V_i yields:

$$e_i(t) = p_i^{\text{ref}}(t) - p_i(t) \tag{9}$$

Substituting (7) gives:

$$e_i(t) = p_h(t-\Theta) - R_i - p_i(t) \tag{10}$$

Assuming that R_i is constant, the time derivatives of the error (10) are:

$$\dot{e}_i(t) = v_h(t-\Theta) - v_i(t) \tag{11}$$

$$\ddot{e}_i(t) = a_h(t-\Theta) - a_i(t) \tag{12}$$

and finally,

$$\dddot{e}_i(t) = -\frac{1}{\tau_h}a_h(t-\Theta) + \frac{1}{\tau_h}u_h(t-\Theta) - \left(-\frac{1}{\tau_i}a_i(t) + \frac{1}{\tau_i}u_i(t)\right) \tag{13}$$

The reference position p_0^{ref} for the platoon leader V_0 is an exogeneous input to the platoon. In contrast to followers, the reference for the leader is neither delayed, nor shifted. Thus, the position error is

$$e_0(t) = p_0^{\text{ref}}(t) - p_0(t) \tag{14}$$

Differentiating the position error three times yields:

$$\dot{e}_0(t) = \dot{p}_0^{\text{ref}}(t) - v_0(t) \tag{15}$$

$$\ddot{e}_0(t) = \ddot{p}_0^{\text{ref}}(t) - a_0(t) \tag{16}$$

$$\dddot{e}_i(t) = \dddot{p}_0^{\text{ref}}(t) + \frac{1}{\tau_0}a_0(t) - \frac{1}{\tau_0}u_0(t) \tag{17}$$

B. Platoon Followers

Considering a control law that compensates for the introduced dynamics of V_h and achieves the desired response of the system is achieved by isolating u_i from (13) and controlling the error dynamics:

$$\begin{aligned} u_i(t) = &-\frac{\tau_i}{\tau_h}a_h(t-\Theta) + \frac{\tau_i}{\tau_h}u_h(t-\Theta) + a_i(t) \\ &+ \tau_i \begin{bmatrix} k_{0,i} & k_{1,i} & k_{2,i} \end{bmatrix} \begin{bmatrix} e_i(t) \\ \dot{e}_i(t) \\ \ddot{e}_i(t) \end{bmatrix} \end{aligned} \tag{18}$$

Inserting (18) into (13) yields

$$\dddot{e}_i(t) = -\begin{bmatrix} k_{0,i} & k_{1,i} & k_{2,i} \end{bmatrix} \begin{bmatrix} e_i(t) \\ \dot{e}_i(t) \\ \ddot{e}_i(t) \end{bmatrix} \tag{19}$$

and results in the error differential equation

$$\dddot{e}_i(t) + k_{2,i}\ddot{e}_i(t) + k_{1,i}\dot{e}_i(t) + k_{0,i}e_i(t) = 0 \tag{20}$$

The controller coefficients $k_{0,i}, k_{1,i}$ and $k_{2,i}$ can be chosen by pole-placement. The characteristic polynomial of (20) is:

$$s^3 + k_{2,i}s^2 + k_{1,i}s + k_{0,i} \tag{21}$$

the desired characteristic polynomial

$$\prod_{j=1}^{3}(s-\alpha_{j,i}) = (s-\alpha_{1,i})(s-\alpha_{2,i})(s-\alpha_{3,i}) \tag{22}$$

$$\begin{aligned} &= s^3 + (-\alpha_{1,i} - \alpha_{2,i} - \alpha_{3,i})s^2 \\ &\quad + (\alpha_{1,i}\alpha_{2,i} + \alpha_{1,i}\alpha_{3,i} + \alpha_{1,i}\alpha_{3,i})s \\ &\quad - \alpha_{1,i}\alpha_{2,i}\alpha_{3,i} \end{aligned} \tag{23}$$

By coefficient comparison, the controller coefficients in (21) can be read from (23) as:

$$k_{0,i} = -\alpha_{1,i}\alpha_{2,i}\alpha_{3,i} \tag{24}$$

$$k_{1,i} = \alpha_{1,i}\alpha_{2,i} + \alpha_{1,i}\alpha_{3,i} + \alpha_{1,i}\alpha_{3,i} \tag{25}$$

$$k_{2,i} = -\alpha_{1,i} - \alpha_{2,i} - \alpha_{3,i} \tag{26}$$

One should note that no current information of the preceding vehicle V_h is required to determine the control input (18) of V_i, but only vehicle states and controller output that are delayed by Θ_i. Thus, the controller is *per design* robust against delays θ_{comm} that occur during (wireless) transmission, as long as $\theta_{\text{comm}} < \Theta_i$.

C. Platoon Leader

For the platoon leader, the following control law is proposed, following the same rational as in (18):

$$u_0(t) = \tau_0\dddot{p}_0^{\text{ref}}(t) + a_0(t) + \tau_0 \begin{bmatrix} k_{0,0} & k_{1,0} & k_{2,0} \end{bmatrix} \begin{bmatrix} e_0(t) \\ \dot{e}_0(t) \\ \ddot{e}_0(t) \end{bmatrix} \tag{27}$$

Inserted in (17) yields

$$\dddot{e}_0(t) = -\begin{bmatrix} k_{0,0} & k_{1,0} & k_{2,0} \end{bmatrix} \begin{bmatrix} e_0(t) \\ \dot{e}_0(t) \\ \ddot{e}_0(t) \end{bmatrix} \tag{28}$$

Again, the controller coefficients can be chosen by pole-placement. The corresponding error differential equation, characteristic polynomial etc. are analogously to (20)–(23) and yield the same results as in (24)–(26).

V. Stability Analysis

To analyse the stability properties of the proposed control scheme, both individual vehicle stability and string stability of the platoon as a whole are analysed.

By choosing all poles α of the error differential equations (20) and (28) strictly in the left-hand plane, vehicle stability and exponentially asymptotic converging behavior to the reference trajectory is ensured.

String stability in platooning is understood as non-amplifying propagation of disturbances from the leader towards the end of the platoon. The corresponding analysis is usually performed by determining the ratio G of the transfer functions $H(s)$ of two succeeding vehicles. The condition for string stability is:

$$G_i(\mathrm{j}\omega) = \left| \frac{H_i(\mathrm{j}\omega)}{H_{i-1}(\mathrm{j}\omega)} \right| \leq 1 \,\forall\, 1 < i < N \tag{29}$$

This is only applicable for vehicle followers, hence only the impact of controller (18) needs to be considered. As the controller compensates the impact of different τ_i along the vehicle string the transfer functions are alike, making the platoon homogeneous. Choosing all free parameters, such as controller gains $k_{j,i}$, delays Θ_i, buffer distances R_i leads to identical transfer functions for all $V_i, i > 0$ and thus a ratio $G = 1$, making the followers of the platoon string stable.

Because the dynamics of the leader reduce to the same error differential equation as for its followers, the ratio between $H_0(\mathrm{j}\omega)$ and $H_1(\mathrm{j}\omega)$ is also one. Thus, the platoon is string stable without dampening the desired response towards the end of the vehicle string. For large platoons this also results in a well-scaling behavior as each vehicle delivers the same response, only delayed by Θ_i and shifted by R_i.

VI. Homogenization and Constrained Control

As shown, the compensation leads to an identical response of each follower to its respective predecessor. Hence, the control scheme can also implement in a leader-follower (LF) communication topology, as each follower accumulates the delays and spatial shifts with relation to the platoon leader V_0 as in:

$$\Theta_i^{\mathrm{LF}} = \sum_{j=1}^{i} \Theta_j \tag{30}$$

$$R_i^{\mathrm{LF}} = \sum_{j=1}^{i} R_j \tag{31}$$

However, this only holds true for followers that allow arbitrary large control inputs. When heterogeneity from different actuation saturation ($\overline{u}$ and $\underline{u}$) occur in the platoon, it is advisable to implement the homogenization scheme. This is based on our findings of inherent homogenization in heterogeneous platoons in [1] and our matching control scheme in [2]. Inherent homogenization occurs when a more limited vehicle (in terms of lag or acceleration and deceleration limits) imposes bounds for feasible tracking. It was shown that introducing homogenization leaders (hL) to a heterogeneous platoon yields performance improvements. In [1], the respective hL are identified based on its acceleration/deceleration capacity. As we have developed a controller (18) that compensates the heterogeneity in actuation lag, the method can be applied to the present case. Thus, (30) and (31) are templates to implement a homogenization leader following (hLF) scheme. To this end, j has not necessarily to be equal to one (to track the platoon leader), but to the respective homogenization leader of vehicle V_i. To implement homogenization leaders, $j = i_{\mathrm{hL}} + 1$ for each V_i.

To implement safety features that account for heterogeneity in braking capacity of the individual platoon members as well as to improve performance metrics such as controlled

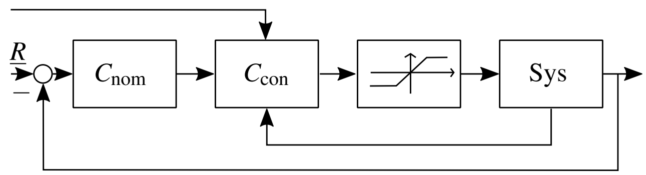

Fig. 3. Constrained control scheme for vehicle control after [2]. The nominal control output C_{nom} is subjected to a set of constraints that provide safety and performance features by C_{con}. This output is limited by $\overline{u}$ and $\underline{u}$ before applied to the system.

catching up when a vehicle has insufficient acceleration capacity, (higher order) zeroing barrier functions ((HO)ZBF) are implemented as in [2]. Fig. 3 shows the control structure of such a controller. In short, the invariance controller C_{con} imposes constraints on the nominal controller C_{nom} to ensure feasibility and safety to the system. The constraints are fed by external conditions as well as internal vehicle states.

Combining the methods of constrained control with the homogenization scheme results in a safe homogenization leader predecessor following (hLPF) scheme as in [2].

VII. Simulation

The following simulation examples evaluate the performance of a heterogeneous platoon with $N = 8$ members. The parameters of the dynamics of the three employed vehicle types are shown in Table I. One should note, that for the given model (5), $\overline{u} = \overline{a}$ and $\underline{u} = \underline{a}$. Table II shows the applied vehicle order. This vehicle order has been chosen to showcase the capacity of the controller to mitigate the effects that arise from a disadvantageous vehicle order along the string in the sense of [11].

The spatial shift and time-delay are homogeneous for all vehicles, i. e. $R_i = R = 5\,\mathrm{m}$ and $\theta_i = \theta = 1\,\mathrm{s}$ for all $V_i, i = 1, \dots, N-1$. The poles of the error dynamics (22) are chosen for a response that is slightly larger than the limits of $\overline{u}$ and $\underline{u}$, respectively, as $\alpha_{1,i} = \alpha_{2,i} = \alpha_{3,i} = -1 \,\forall\, i$, so that $k_{0,0} = k_{0,i} = 1$, $k_{1,0} = k_{1,i} = 3$, and $k_{2,0} = k_{2,i} = 3$.

A. Simulation setup

The reference profile is designed along our observations in [2] with a feasible reference profile, i. e. the reference

TABLE I
Vehicle Dynamics

Type		Time constant τ	Pos. limit $\overline{a}$	Neg. limit $\underline{a}$
Car	I	$0.1\,\mathrm{s}$	$2.0\,\mathrm{m/s^2}$	$-6.0\,\mathrm{m/s^2}$
LDV	II	$0.2\,\mathrm{s}$	$1.5\,\mathrm{m/s^2}$	$-5.0\,\mathrm{m/s^2}$
HDV	III	$0.3\,\mathrm{s}$	$1.0\,\mathrm{m/s^2}$	$-4.0\,\mathrm{m/s^2}$

TABLE II
Vehicle Order

	0	1	2	3	4	5	6	7
Color								
Type	I	I	II	II	III	III	I	II
hL	p_{ref}	V_0	V_0	V_2	V_2	V_4	V_4	V_4

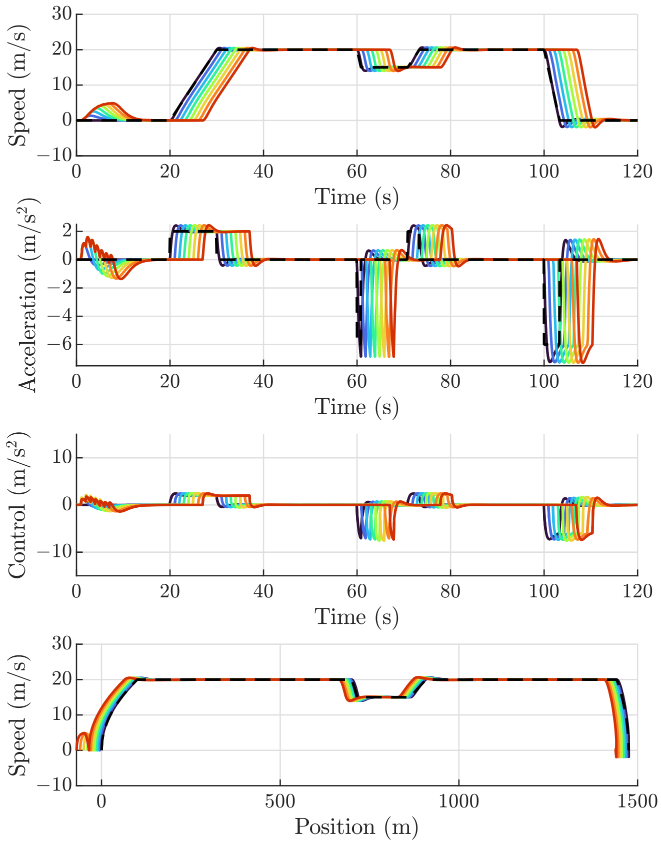

Fig. 4. Heterogeneous platoon response in PF configuration, without saturation. The compensation yields an identical response in time (control input, acceleration, speed). The bottom plot shows the speed tracking referred to the position along the route, shifted by R_i.

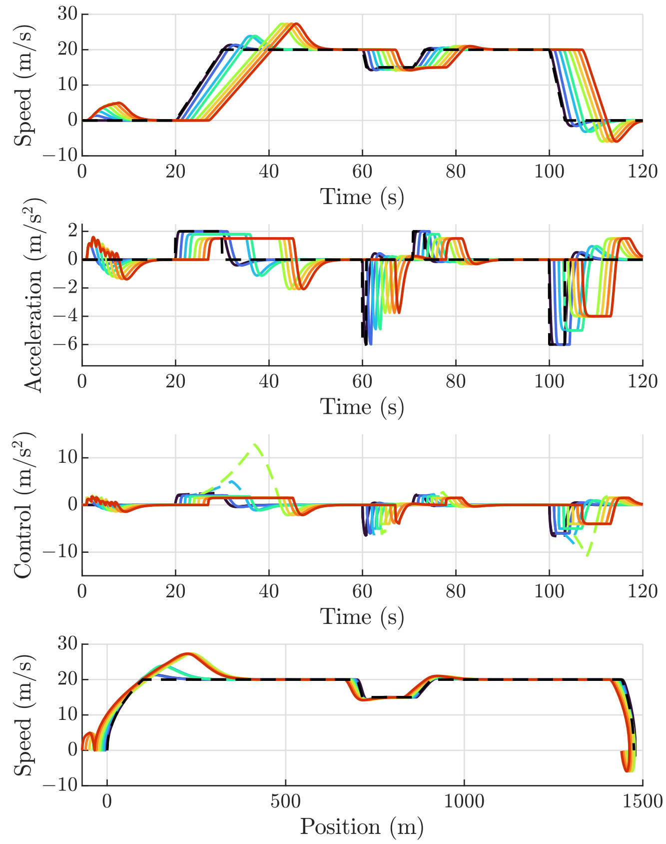

Fig. 5. As in Fig. 4, with saturations as per Table I. The saturation effect impedes the tracking. $V_5 \dots V_7$ display effects of the inherent homogenization caused by V_4.

considers the acceleration and deceleration capacity $\overline{a}_0$, and $\underline{a}_0$ of the platoon leader. There are several phases of the platoon mission. First, the vehicles $V_1, \dots, V_7$ as followers form a platoon behind the leader V_0. They do so from standstill and positions that differ from their nominal starting positions. After the platoon has formed, the mission starts at $t = 20\,\mathrm{s}$. It then tracks the reference profile to reach a cruising speed of $v_{\mathrm{cc}} = 20\,\mathrm{m/s}$. At $t = 60\,\mathrm{s}$ the profile imposes a reduction of the reference speed to $15\,\mathrm{m/s}$, before speeding up again. The mission finishes with braking at $t = 100\,\mathrm{s}$ and finally coming to a stop at the reference position.

B. Discussion

Fig. 4 showcases the performance of the compensating controller (18) and (27). Per definition, this results in a PF topology, i.e. $h = i - 1$ for $i = 1, \dots, N-1$. The time shift caused by the delay Θ_i is clearly visible in the speed and acceleration plots. The plot of the control input over time shows that the effort depends on the compensation for different τ_i along the vehicle string to yield the desired response. Finally, the speed over position plot reveals the spatial shift caused by R_i. Yet, the platoon tracks the desired response reasonable well, as R_i is small compared to the travelled distance.

Fig. 5 shows the influence of different saturation limits for acceleration and control input, respectively. As expected, the steep acceleration phase ramping up to cruising speed is infeasible for the heavier vehicles of type II and III. As a result, these need to catch up to the leading section of the platoon. Yet, it is visible, that spatial tracking of the reference speed is asymptotically achieved. Moreover, more agile vehicles at the end of the vehicle string (here: V_6 and V_7) deliver a reduced control effort compared to the more sluggish mid section (V_4 and V_5). The effect of saturation is indicated by dashed lines (deviation from non-saturated controller output).

Fig. 6 shows the response of a homogenized platoon with constrained control of the nominal linear controller, including saturation limits and acceleration, speed, and braking distance constraints. The effects of homogenization are visible in the reduced control effort towards the end of the platoon. The deviation from the nominal control output to the constrained and saturated output is also reduced compared to Fig. 5. The constraints become visibly effective during the catch-up phase as the maximum speed is limited to $\overline{v} = 22\,\mathrm{m/s}$. While the acceleration limits are preserved, the agile vehicles at the end of the platoon can still exploit their large dynamic range to maintain save braking distance towards a sluggish platoon member. Compared to Fig. 5, the amount

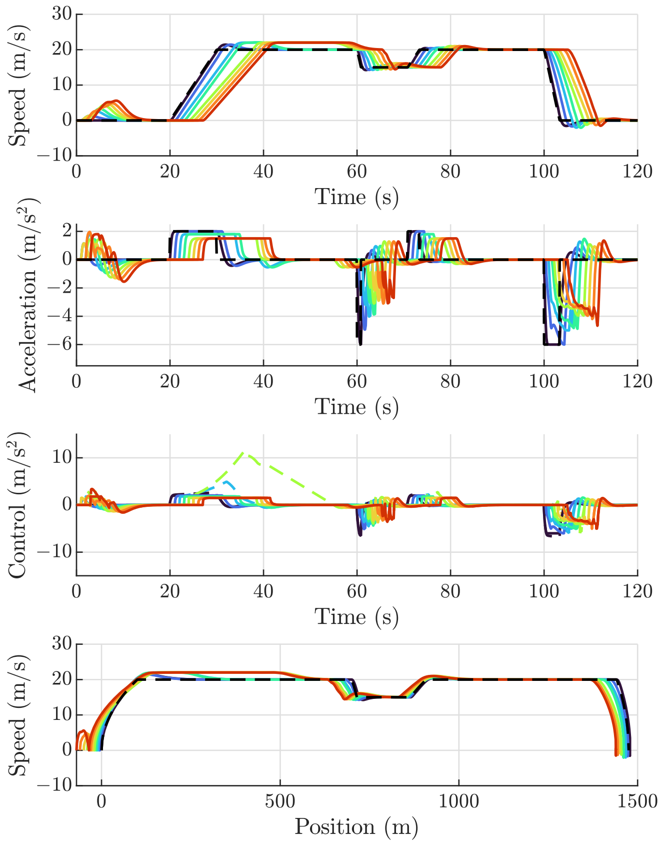

Fig. 6. Heterogeneous platoon response in hLPF configuration, including saturation and constraints.

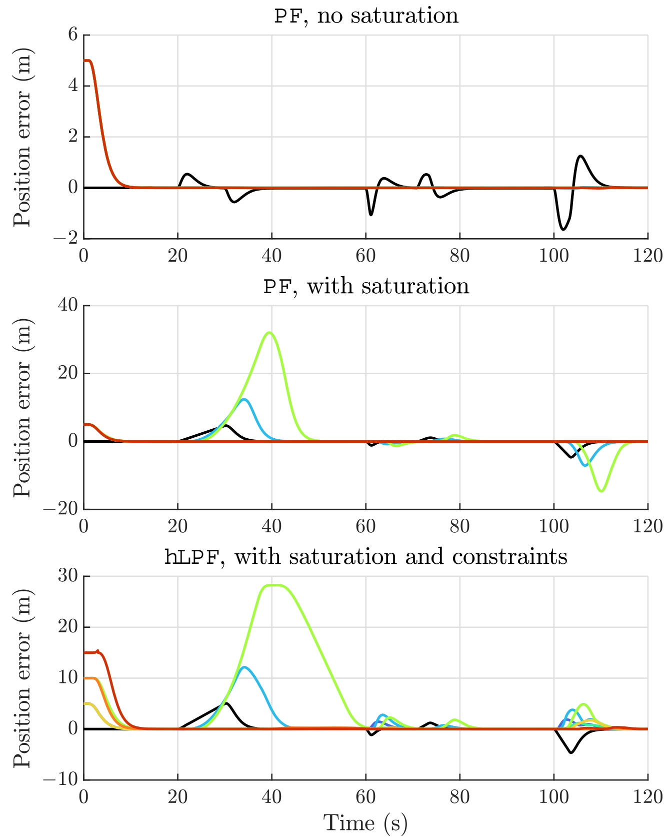

Fig. 7. Position errors for the different cases. Top: PF without actuation saturation or constraints, middle: PF with saturation and without constraints, bottom: hLPFwith saturation and constraints.

of overshoot in position is largely reduced which leads to lower negative vehicle speed. However, with the current implementation overshoot can not entirely be removed. The tracking controllers do not employ a preview of the trajectory and hence must overshoot when reaching the end position at a non-zero speed.

Fig. 7 compares the position errors for the different cases (note the different range on the ordinate axis). As the chosen reference trajectory is not sufficiently smooth, the leader exhibits some overshoot, since (27) depends not only on the position, but also on the derivatives of the trajectory. In contrast, the followers then are referenced to the sufficiently smooth trajectory of the leader. The PF case shows that after forming of the platoon (during $t = [0, 10]\,\mathrm{s}$) virtually no position error is present, demonstrating the tracking property of controller (18). The PF case with active saturation to $\underline{u}_i$ and $\overline{u}_i$ reveals the negative effects of heterogeneous saturation along the vehicle string. Not only leads it to large separation during catching up ($t = [20, 50]\,\mathrm{s}$) but also to large position errors when stopping ($t = [100, 120]\,\mathrm{s}$). The hLPF case with saturation and constraint enforcement is not entirely free of the separation due to the lack of upstream links within the platoon but the magnitude is reduced. Also and more significantly, the position error of $V_1, \ldots, V_7$ remain semi-definitely positive, meaning that the safety distances are maintained throughout the platoon mission.

VIII. Conclusion

In this paper, a modified delay-based spacing policy has been proposed that enables missions of a platoon including forming, standstill and maneuver control. To this end, a linear controller with an exogenous input has been presented, that compensates the heterogeneity from drivetrain dynamics of the platoon members. The design was then enhanced by introducing homogenization to the different non-linear actuation limits and augmented by constrained control to improve the driving behavior. The performance of the control scheme was evaluated by simulation.

For future work different functions for r_i or R_i shall be considered. For instance, the spacing could be chosen to yield a non-zero distance at low vehicle speed $r_i(v \to 0) = r_{i,0} =$ const. and asymptotically converging to $r_i(v \gg 1) = v_h \theta_i$ for the cruising state of the platoon. Furthermore, the HOZBF to implement the safety distance does not consider the increased braking distance caused by the system lag. In the same sense, it was discussed how the spacing policy is by design robust against communication delays. However, to implement the (HO)ZBF, the constraint enforcement relies on current states and measurements. It is advisable to consider alternative schemes to access these information, e. g. by utilizing observers or methods of adaptive control. This may also be advisable, as the exact knowledge of the vehicle lag τ_i is essential for the control design yet is difficult to assess *a priori* in practice.

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